

# Do Multi-planet Extrasolar Systems Contain Terrestrial Planets?

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# Introduction

All the extrasolar planetary systems around main sequence and subgiant stars have been detected with the precision radial velocity technique. This method, which favors the detection of close-in giant planets, is currently unable to detect terrestrial planets or distant gas giants. Although continued observations should help with this insensitivity, some of the distant gas giants, as well as terrestrial planets, are more amenable to detection with other techniques and future space-based missions, such as DARWIN and TPF.

Here we look at the stability of test particles (massless and non-interacting) in four of the extrasolar planetary systems: GJ 876,  $\nu$  Andromedae, 47 Uma, and 55 Cancri. The results of the simulations presented here can be used to look for regions in these systems where a terrestrial planet may be stable.

# Methodology

We performed N-body simulations of the planetary systems in orbit about the stars 47 Uma, 55 Cancri, GJ 876, and  $\nu$  Andromedae. To determine regions in these systems where a terrestrial planet could have a stable orbit, we placed several test particles in these systems and integrated their orbits. All test particles were started on circular orbits with respect to the central star in the plane of the system. No test particles were placed on orbits that initially crossed the orbit of a planet.

In order to generate the initial conditions for the planets, we performed dynamical fits to the radial velocity data for the four stars using a Levenberg-Marquardt minimization algorithm. We only fit for the planetary masses ( $m_{\text{pl}}$ ), the semi-major axes ( $a$ ), the eccentricities ( $e$ ), the arguments of periastron ( $\omega$ ), and the mean anomalies ( $M$ ) for each planet.

The simulations were performed with the second-order mixed variable symplectic (MVS) integrator in the MERCURY integration package. This code was modified to include the relativistic precession of the longitudes of periastron.

## Tables of Fitted Astrocetric Parameters

### Parameters for $\nu$ Andromedae

Parameter	inner	middle	outer
$m_{\text{pl}} (M_{\text{Jup}})$	0.65	1.80	3.59
$a$ (AU)	0.0577	0.807	3.43
$e$	0.0112	0.276	0.268
$\omega$ (deg)	53.8	249.9	261.2
$M$ (deg)	215.4	119.4	337.6



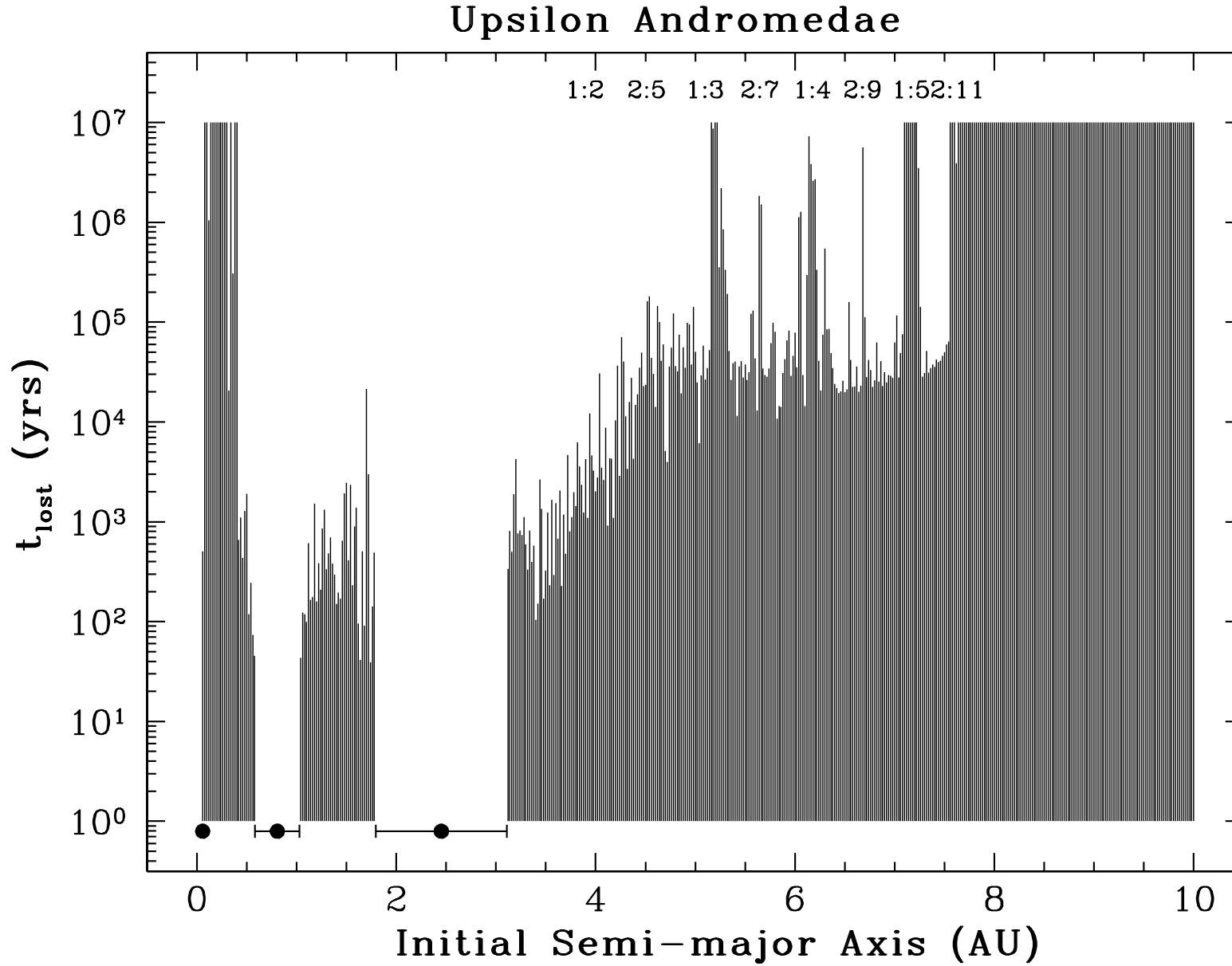


Figure 1: Lifetimes of test particles in the  $\upsilon$  Andromedae system as a function of particle initial semi-major axis. Particles were placed on circular orbits in the plane of the system with semi-major axes ranging from 0.06 AU to 10.00 AU at intervals of 0.02 AU, excluding the initial range of distances covered by the outer two planets.

## Parameters for GJ 876

Parameter	inner	outer
$i = 90^\circ$		
$m_{\text{pl}} (M_{\text{Jup}})$	0.59	1.88
$a$ (AU)	0.130	0.208
$e$	0.224	0.0152
$\omega$ (deg)	330.1	318.6
$M$ (deg)	164.8	271.6
$i \approx 39.6^\circ$		
$m_{\text{pl}} (M_{\text{Jup}})$	0.90	2.96
$a$ (AU)	0.130	0.209
$e$	0.288	0.0379
$\omega$ (deg)	329.6	302.2
$M$ (deg)	165.2	282.1

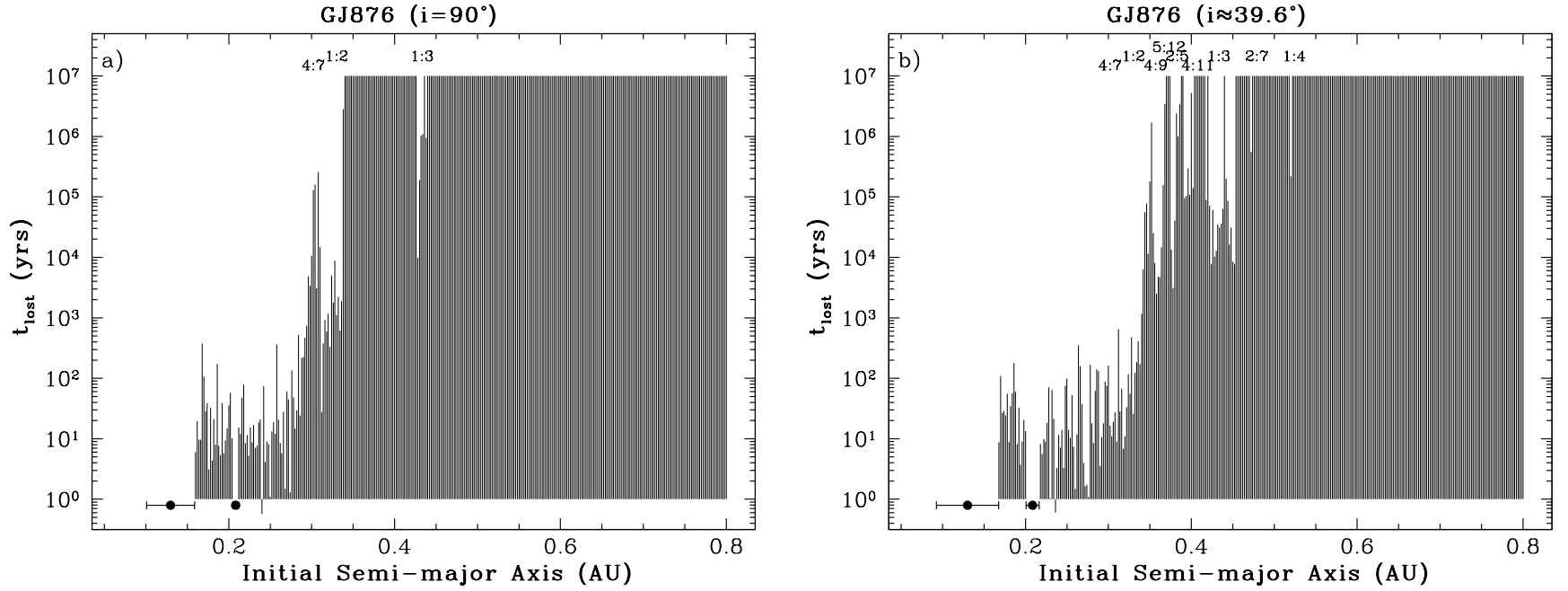


Figure 2: Lifetimes of test particles in the GJ 876 system for (a)  $i = 90^\circ$  and (b)  $i \sim 39.6^\circ$  as a function of particle initial semi-major axis. Particles were placed on circular orbits in the plane of the system with semi-major axes ranging from just exterior to the orbit of the inner planet to 0.800 AU at intervals of 0.002 AU, excluding the initial range of distances covered by the outer planet.

## Parameters for 47 Uma

Parameter	inner	outer
$m_{\text{pl}} (M_{\text{Jup}})$	(2.72)	1.02
$a$ (AU)	(2.09)	4.47
$e$	(0.0466)	0.00000597
$\omega$ (deg)	(108.2)	328.6
$M$ (deg)	(270.6)	330.7

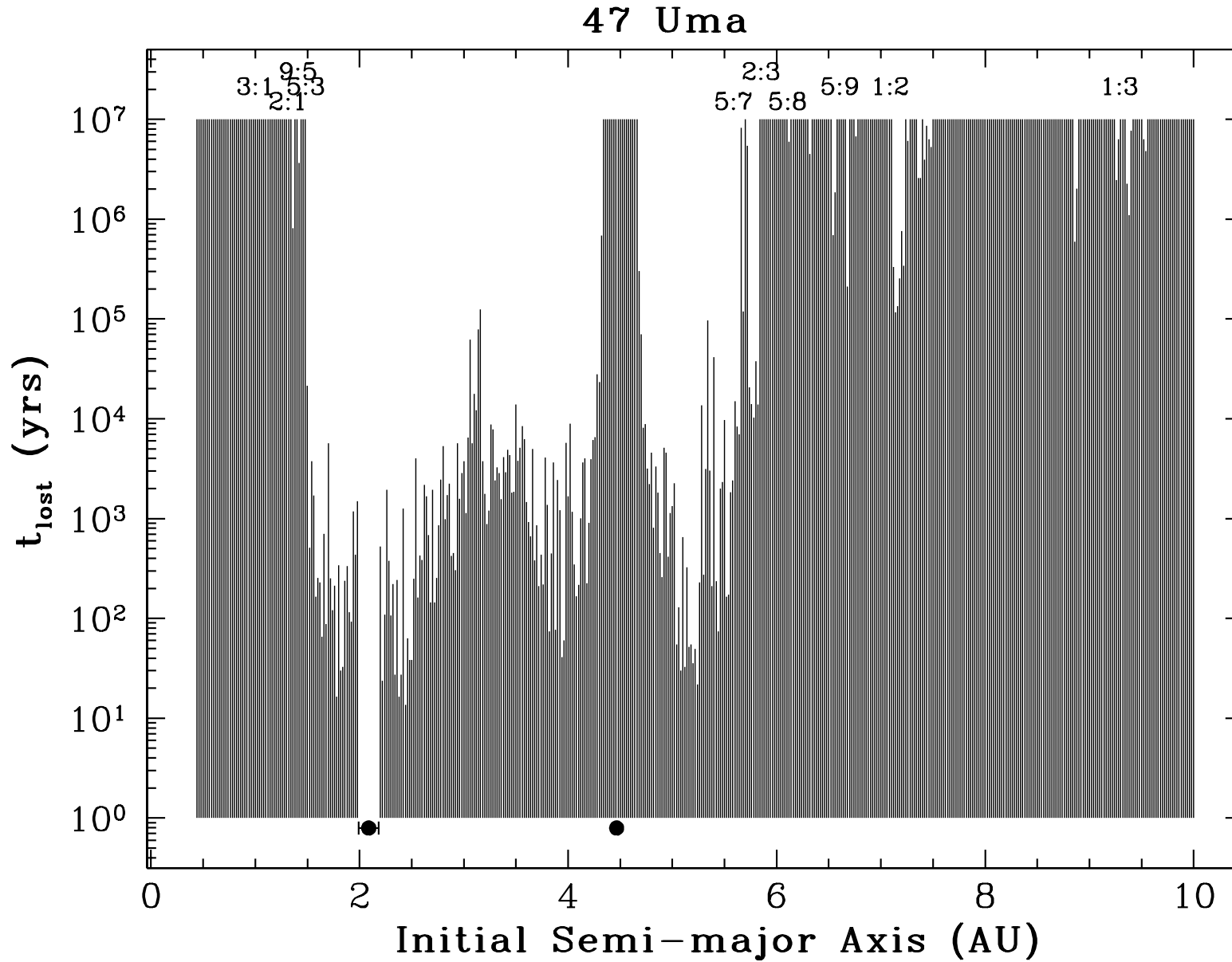


Figure 3: Lifetimes of test particles in the 47 Uma system as a function of particle initial semi-major axis. Particles were placed on circular orbits in the plane of the system with semi-major axes ranging from 0.44 AU to 10.00 AU at intervals of 0.02 AU, excluding the initial range of distances covered by the outer planet.

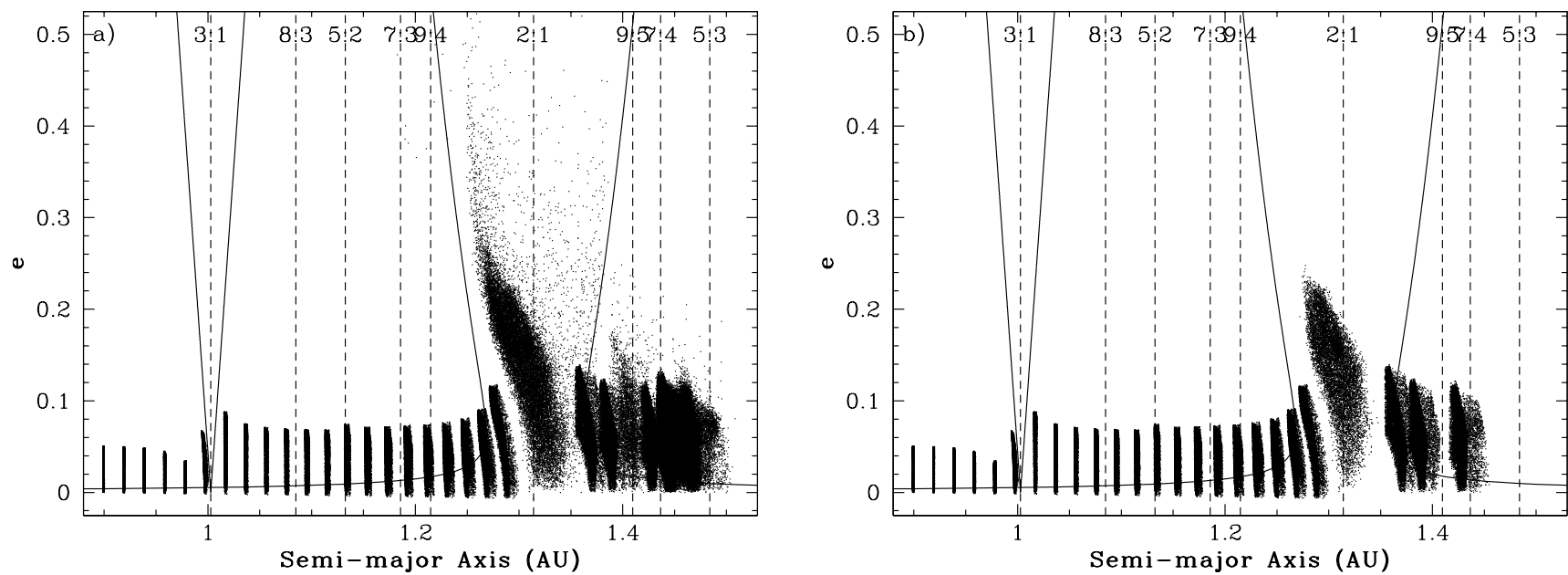


Figure 4: Eccentricity vs. semi-major axis for test particles with initial semi-major axes in the range 0.90 AU to 1.50 AU in the 47 Uma system. a) all test particles, b) only test particles which survived 100 Myr are shown.

## Parameters for 55 Cancri

Parameter	inner	middle	outer
$m_{\text{pl}} (M_{\text{Jup}})$	0.82	0.18	3.74
$a$ (AU)	0.115	0.240	5.49
$e$	0.0657	0.201	0.244
$\omega$ (deg)	122.4	33.8	196.5
$M$ (deg)	34.7	29.7	187.8

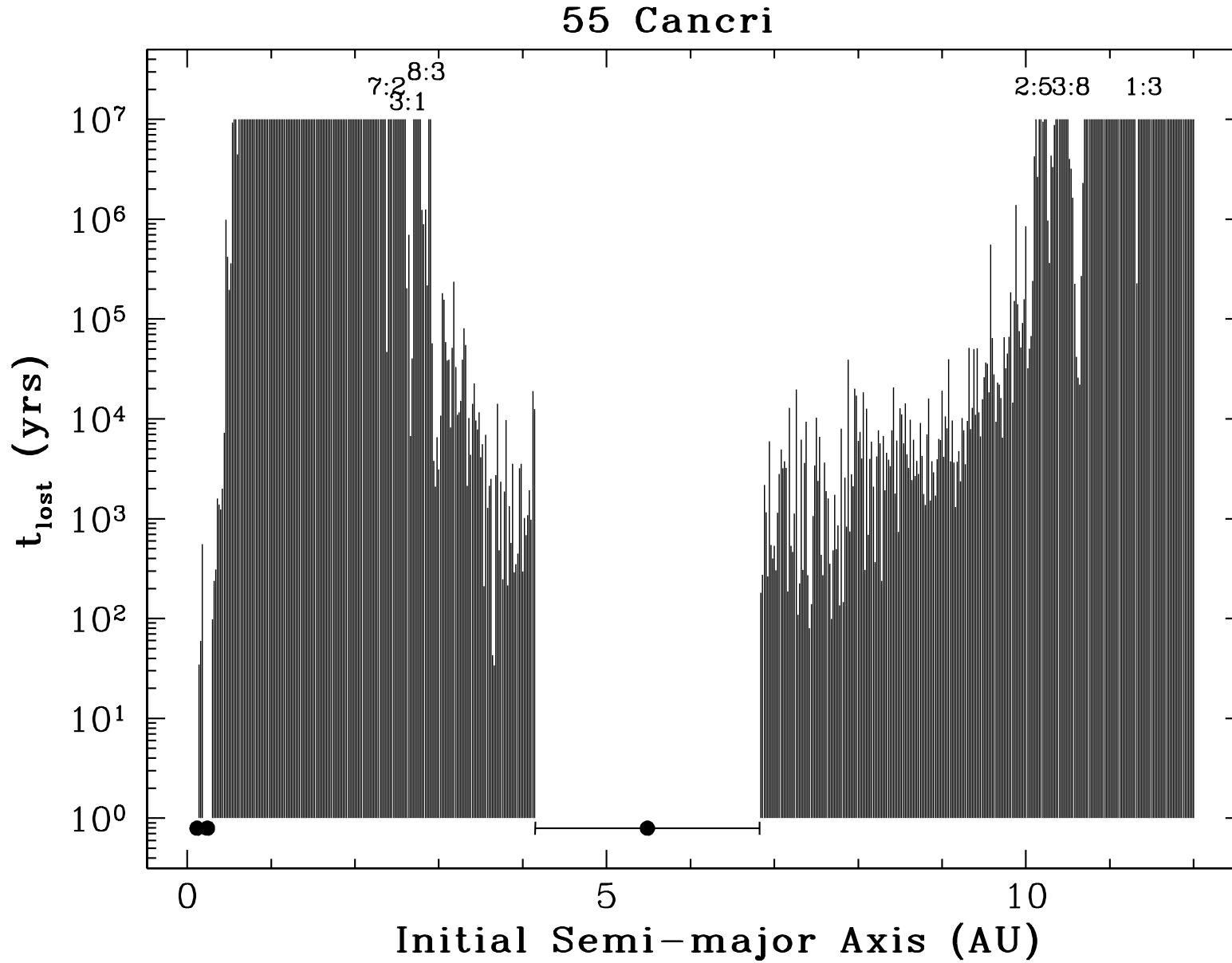


Figure 5: Lifetimes of test particles in the 55 Cancri system as a function of particle initial semi-major axis. Particles were placed on circular orbits in the plane of the system with semi-major axes ranging from 0.14 AU to 12.00 AU at intervals of 0.02 AU, excluding the initial range of distances covered by the outer two planets.



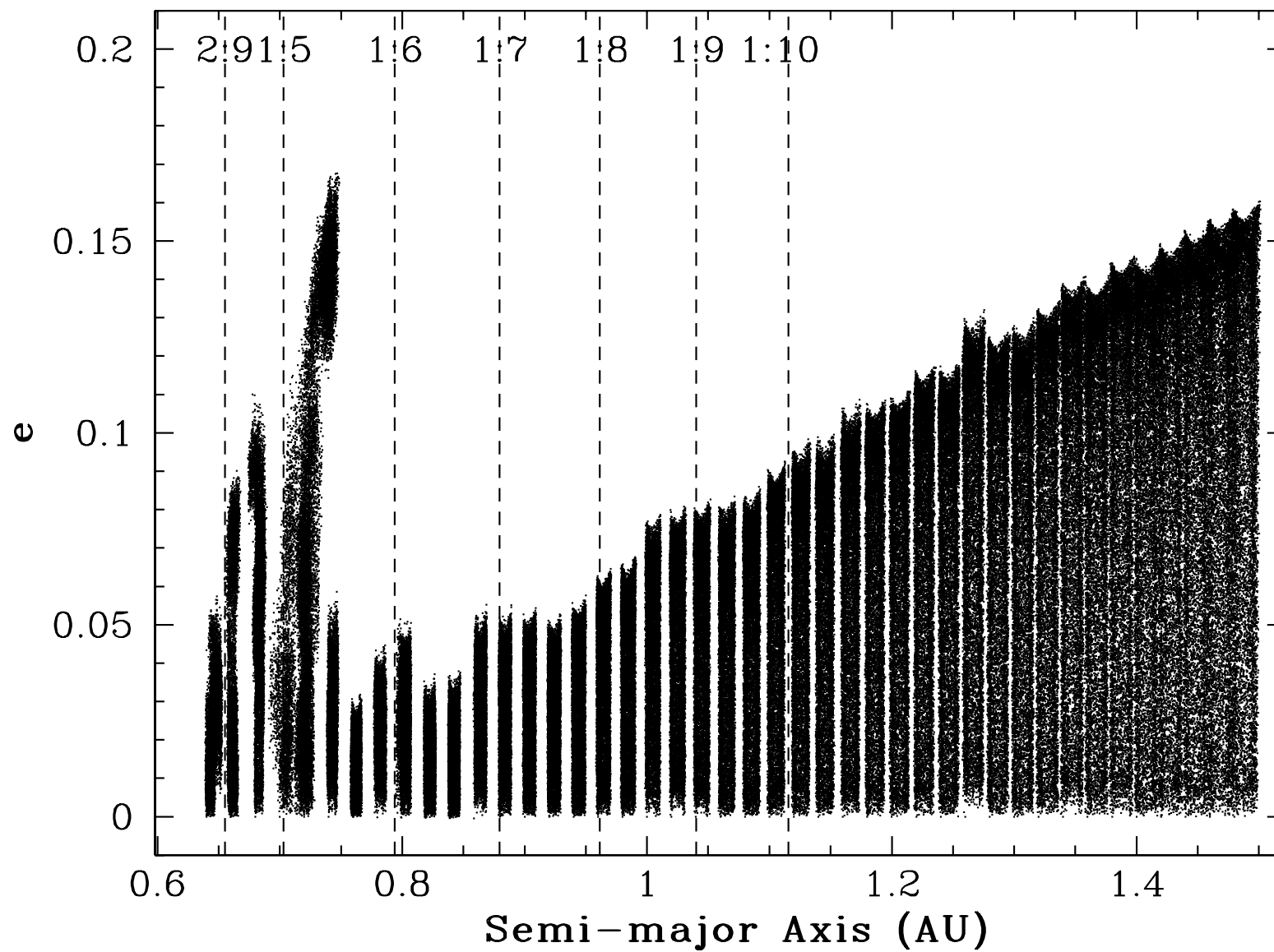


Figure 6: Eccentricity vs. semi-major axis for test particles with initial semi-major axes in the range 0.64 AU to 1.48 AU in the 55 Cancri system.

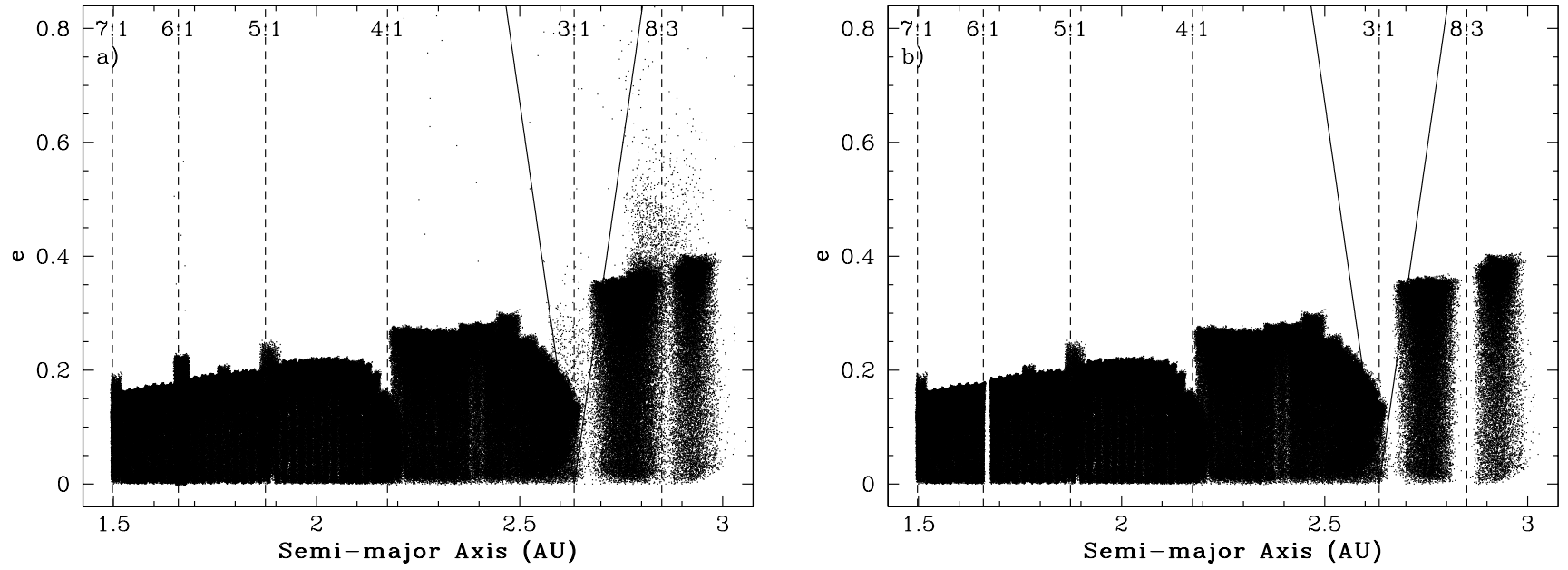


Figure 7: Eccentricity vs. semi-major axis for test particles with initial semi-major axes in the range 1.50 AU to 2.90 AU in the 55 Cancri system. a) all test particles, b) only test particles which survived 100 Myr are shown.

## Summary

- Most particles placed in regions between planets are unstable on timescales of  $< 10^5$  years.
- Three exceptions were the region just outside the orbit of the inner planet in  $\nu$  Andromedae, some captured Trojans in 47 Uma, and the region between the middle and outer planets in 55 Cancri.
- No test particles in the habitable zones of  $\nu$  Andromedae and GJ 876 were stable.
- There were several stable particles in the habitable zones of 47 Uma and 55 Cancri; however, it is unlikely that terrestrial planets in the habitable zones of 47 Uma and 55 Cancri would have survived the formation of these systems.

- Based on this work, the currently known multi-planet extrasolar systems could harbor more planets in one of four types of regions:
  - distant orbits
  - close-in orbits (even if the system already has a jovian mass planet very close to the star as in  *$\nu$  Andromedae*)
  - for systems with widely spaced planets, additional planets may exist between them
  - it is possible that small planets may exist in regions where they could be protected from close encounters with their jovian neighbors by resonances.